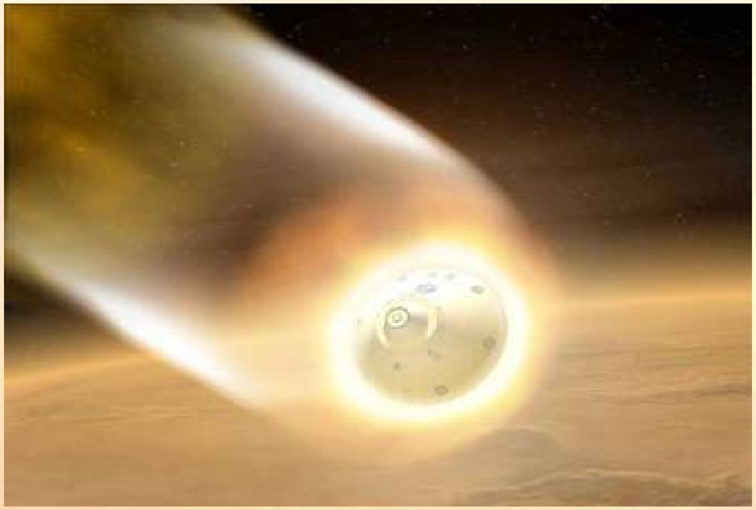


Mars Entry Atmospheric Data System (MEADS) Requirements and Design for Mars Science Laboratory (MSL)

Michelle Munk, Mark Hutchinson, Michael Mitchell, Peter Parker, Alan Little, Jeff Herath, Walter Bruce, Neil Cheatwood

NASA Langley Research Center, Hampton, VA

6th International Planetary Probe Workshop | Atlanta, GA | June 25, 2008

Outline

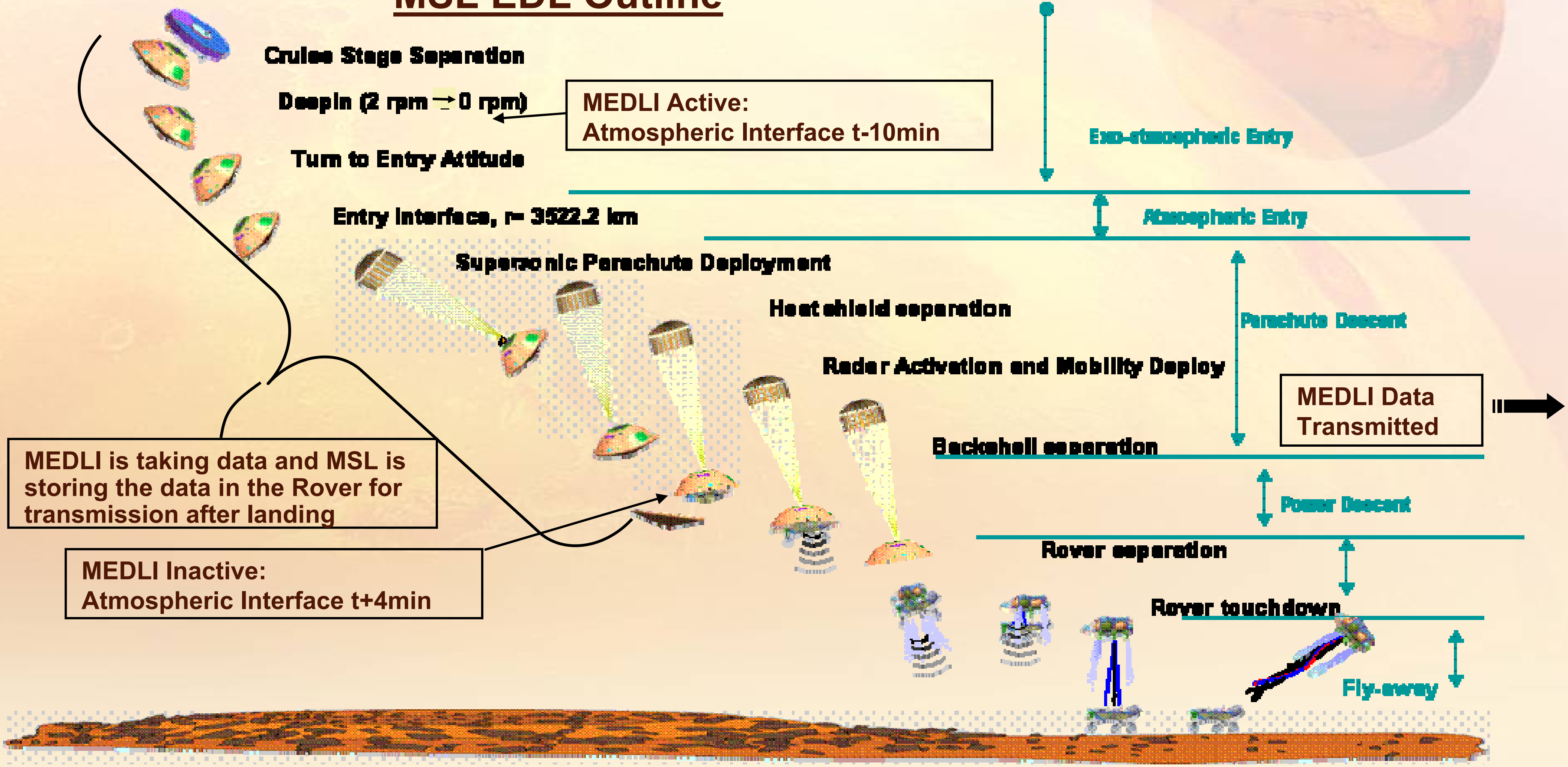
- What is MEDLI?
- MEADS requirements and testing
  - MSL system aspects
  - MEADS performance aspects
    - Transducers
    - Port hole
  - Environmental Testing
- Recent and Near-Term MEADS activities

MSL Entry, Descent, and Landing Instrumentation (MEDLI) Rationale

- MSL is taxing the limits of current modeling capabilities for Mars entry missions
  - Aeroheating uncertainties are greater than 50% on heatshield, due to early transition to turbulence, surface chemistry, and ablation induced roughness.
- A primary source of uncertainty is a lack of relevant flight data for improved model validation
  - A small amount of Thermal Protection System (TPS) performance data was obtained from Pathfinder, but no direct measurements of aeroheating, aerodynamics, or atmosphere.
- MEDLI is a suite of instrumentation embedded in the heatshield of the MSL entry vehicle
  - Measures temperature, TPS recession, and pressure
- MEDLI will collect an order of magnitude more EDL data than all previous Mars missions combined
  - Thermocouple and recession sensor data will significantly improve our understanding of aeroheating and TPS performance uncertainties for future missions.
  - Pressure data will permit more accurate trajectory reconstruction, as well as separation of aerodynamic and atmospheric uncertainties in the hypersonic and supersonic regimes.

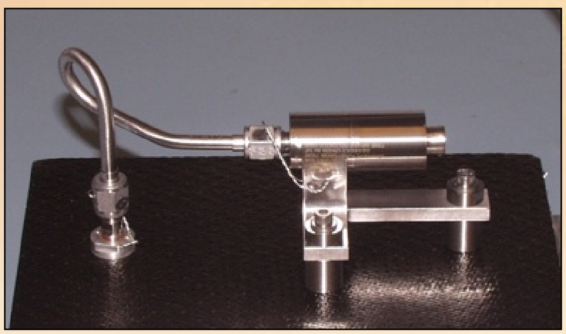
MEDLI Operations Concept During MSL EDL

MSL EDL Outline

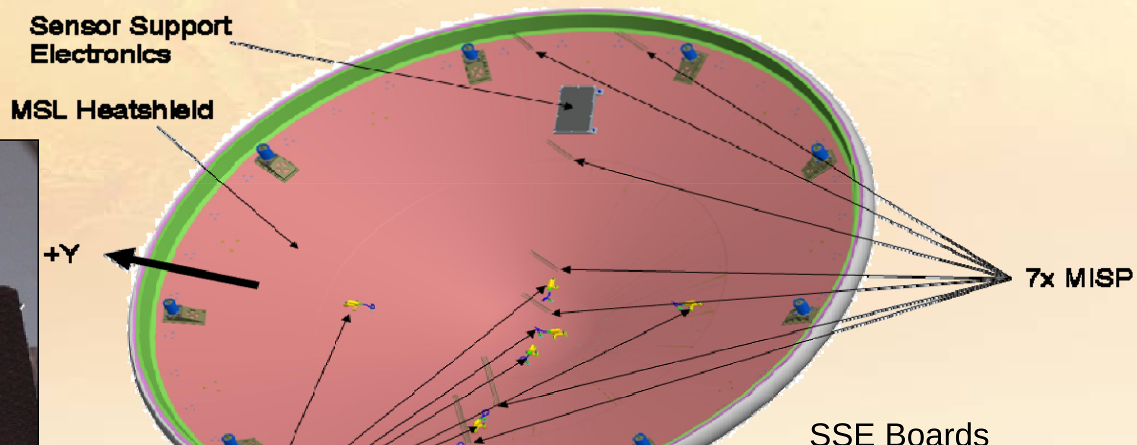


MEDLI System Description: 7 + 7

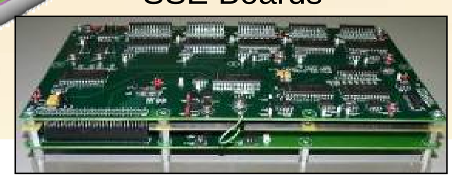
- MEDLI Instrumentation consists of:
  - **7 pressure ports** through heatshield - Mars Entry Atmospheric Data System (MEADS)
  - **7 sensor plugs**, each containing four thermocouples and a recession sensor - Mars Integrated Sensor Plug (MISP)
- **Sensor Support Electronics** provides power to the sensors, conditions and digitizes the sensor signals
- Digitized data stream is sent via MSL's Descent Stage to Rover for storage until the data is telemetered back to Earth after landing



MEADS Assembly



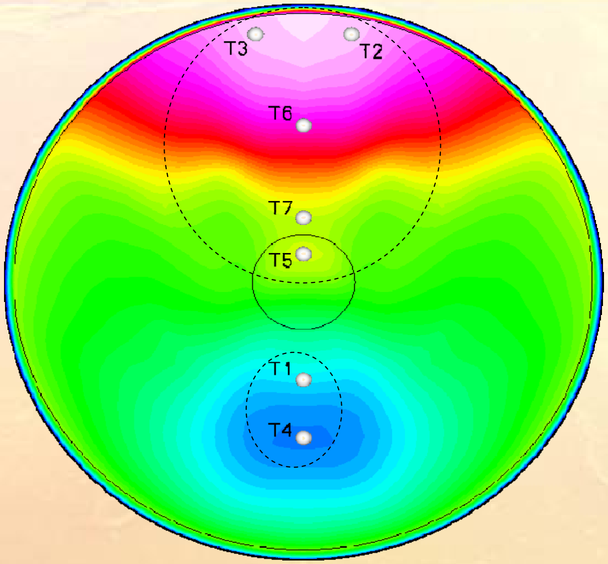
SSE Boards



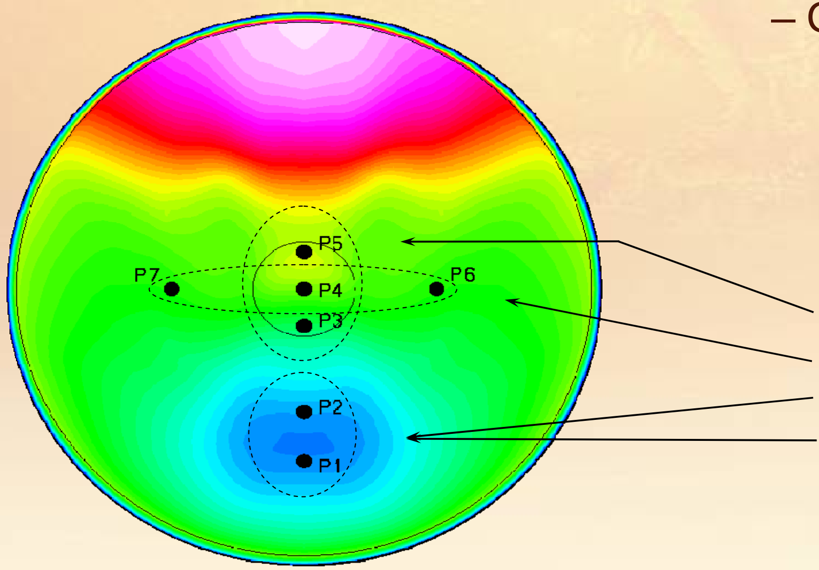
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

MISP Plug

MEDLI Sensor Placement to Meet Science Objectives



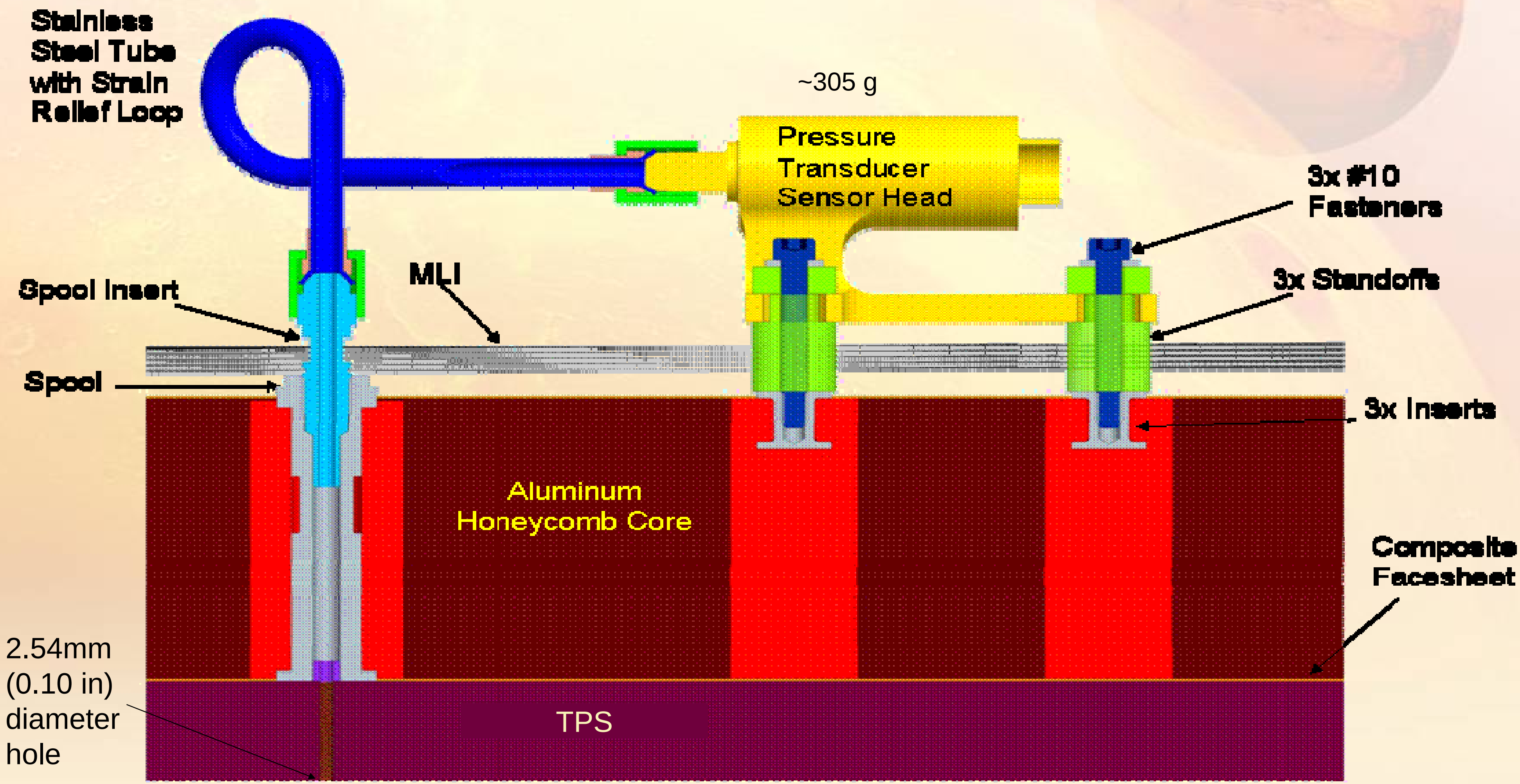
- **Aerodynamics & Atmospheric Objectives (MEADS)**
  - Measure local discrete surface pressure measurements for post flight estimation of:
    - dynamic pressure
    - angle-of-attack
    - angle-of sideslip
  - Separate aerodynamics from atmosphere
  - Determine density profile over large horizontal distance
  - Isolate wind component
  - Confirm aerodynamics at high angles of attack



Aerodynamics/Atmosphere Objectives

Technical Objectives	Location						
	P1	P2	P3	P4	P5	P6	P7
Basic Surface Pressure	X	X	X	X	X	X	X
Angle of Attack	X	X	X	X	X		
Angle of Sideslip				X		X	X
Dynamic Pressure	X	X					
Mach Number	X	X					

MEADS Subsystem Design



MEDLI/MEADS Requirements

- **Overarching MEDLI Requirement: Don't cause harm to MSL**
  - Hole in TPS must be thoroughly tested
  - Hardware must maintain integrity and not impact MSL, through all environments
- Live within 15 kg mass allocation (All of MEDLI) (12.5 kg of removed ballast)
- Stringent PP/CC requirements (100 spores for all of MEDLI)
- **MEADS Performance Requirements**
  - Measure pressures to reconstruct angle of attack (Alpha) within +/- 0.5 degrees where free stream dynamic pressure is greater than [850 Pa].
  - Measure pressures to reconstruct angle of sideslip (Beta) within +/- 0.5 degrees where free stream dynamic pressure is greater than [850 Pa].
  - Measure pressures to reconstruct dynamic pressure (qbar) within +/- 2 percent of measured value where free stream dynamic pressure is greater than [850 Pa].
  - Measure pressures to reconstruct Mach number within +/- 0.1 where free stream dynamic pressure is greater than [850 Pa].

MEADS Requirements

MEDLI Pressure Port Location	The FS shall determine the locations of the centers of all MEDLI pressure ports as installed to within [±1.27 mm] in pre-flight heatshield coordinates.	Must know where ports are located
MEDLI Pressure Port Location Knowledge	The Flight System (FS) shall install each pressure port within [12.7 mm] of its nominal location	Must put ports where expected
MEDLI Pressure Port Diameter	The FS shall provide MEDLI pressure ports with a diameter of [2.54 mm +/- 0.001 mm] through the SLA material.	Must specify diameter to drill
MSL Heatshield Material	The FS shall provide PICA that is consistent with the flight lot PICA.	Must have flight-lot TPS for qual testing.
MEDLI Pressure Port Orthogonality	Each MEDLI pressure port shall be orthogonal to the heatshield surface through the heatshield material [+/- 1.0 degrees].	Keeps port opening circular
MEDLI Pressure Transducer Temperature Knowledge	The temperature of each MEDLI pressure transducer shall be known, [+/- 1°C], during data collection phase	The transducers are calibrated producing curves relative to temperature
MEDLI Pressure Transducer Temperature Sampling Rate	The temperature of each MEDLI pressure transducer head shall be sampled at a minimum rate of [0.2 Hz], during data collection phase	The transducers are calibrated producing curves relative to temperature, so temperature knowledge is needed
MEDLI Pressure Transducer Survival Temperature Range	The temperature of each MEDLI pressure transducer head shall be maintained between [-65 F and 200 F].	To avoid damaging the transducers. We need to monitor.
MEDLI Pressure Transducer Operating Temperature Range	The temperature of each MEDLI pressure transducer head shall be maintained between [-65 F and 200 F] during data collection.	To achieve accuracy requirements. We need to monitor during data collection.
MEDLI Pressure Transducer Electronics Operating Temperature Range	The temperature of each MEDLI pressure transducer electronics shall be maintained between [-54 C and +79 C] during operations.	Min and max for operation from vendor (-65 F to 175 F)
MEDLI Pressure Transducer Electronics Survival Temperature Range	The temperature of each MEDLI pressure transducer electronics shall be maintained between [-54 C and +93 C] at all times.	Survival temps from vendor (-65 F to 200 F)

MEADS Requirements (cont'd)

MEDLI Pressure Path Length	The length of each MEDLI pressure path shall be less than [381 mm (15 in)]	Max Allowable Lag. Approx. 15 in. The goal is to have all ports the same length (not required).
MEDLI Pressure Path Segment Length Knowledge	The length of each MEDLI pressure path segment shall be known to within [2.54 mm (0.1 in)].	To accurately model system response. Segments include but are not limited to: TPS, spool, tubing and transducer.
MEDLI Pressure Path Segment Diameter Knowledge	The diameter of each MEDLI pressure path segment shall be known to within [0.254mm (0.010 in)]	To accurately model system response.
MEDLI Pressure Path Debris	Each MEDLI pressure path shall be kept free of obstructions.	Can only control until launch. Want integrity checks during cruise. Allow for fiberoptic inspection.
MEDLI Pressure Transducer Accuracy	Each MEDLI pressure transducer shall be calibrated to produce outputs that are [+/- 0.5 % of reading] between [850 Pa and 30 kPa]	Accomplished only with additional calibrations
MEDLI Pressure Transducer Input Voltage	The input voltage for each MEDLI pressure transducer shall be [28 V +/- 4V]	
MEDLI Pressure Transducer Input Voltage Knowledge	The input voltage for each MEDLI pressure transducer shall be known within [+/- 0.5V]	We have to ensure this, to achieve 0.5% accuracy.
MEDLI Pressure Transducer Input Voltage Sample Rate	The input voltage for each MEDLI pressure transducer shall be sampled at a minimum rate of [0.2 Hz], during data collection.	

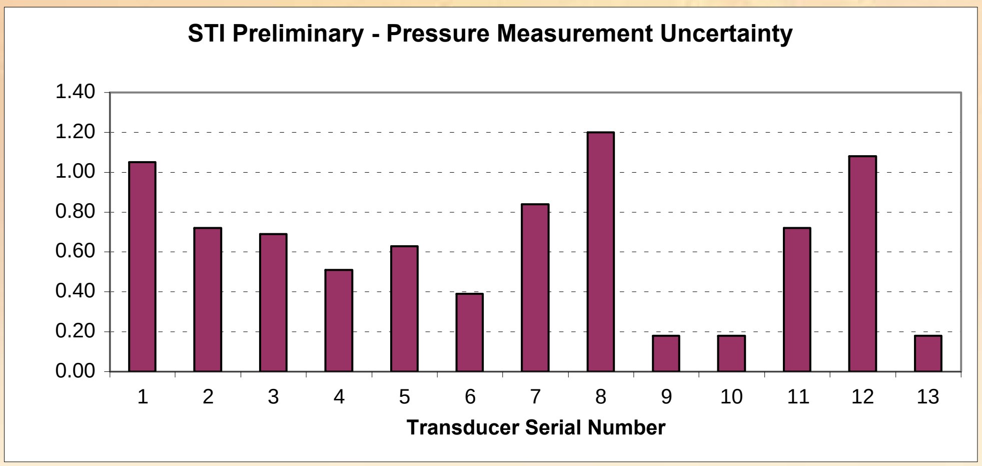
Error Budgeting

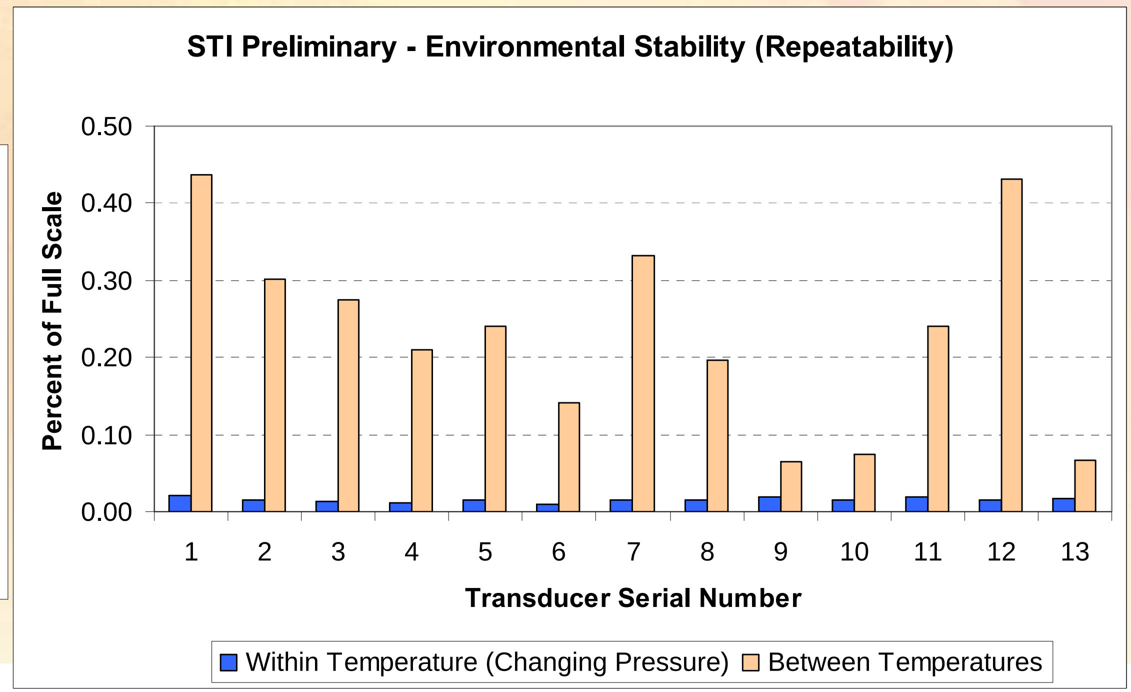
- **Angle of Attack**
Required: +/- 0.5ū 3-sigma
  - Transducer Error
Allocated: +/- 0.25ū 3-sigma
(+/- 0.5% of reading MEDLI-RQ-45)
As Measured: TBD from cal
    - Multiplicative Pressure Bias
Allocated: not explicitly
As Measured: TBD from cal
Results In:
    - Additive Pressure Bias
Allocated: not explicitly
As Measured: TBD from cal
Results In:
    - Transducer Temp Error
Allocated: not explicitly (1ūC reqd-20)
Designed To: 1.1 ūC or +/- 0.4%
Calibrated out via consistent mounting
    - Thermal Transpiration Error
Allocated: not explicitly
As Determined: ~0 from analysis
refine with modeling
    - Pneumatic Lag Error
Allocated: not explicitly
As Determined: ~0 from analysis
      - Path Length Uncertainty
Allocated: not explicitly
Deisgned To: +/- 0.10" (MEDLI-RQ-43)
Results In: TBD
      - Path Diameter Uncertainty
Allocated: not explicitly
Designed To: +/- 0.01" (MEDLI-RQ-76)
Results In: TBD
      - Lag Model Uncertainty
Allocated: not explicitly
As Determined: [TBD]
shock tube test summer 08
  - SSE Error
Allocated: <+/- 0.25ū 3-sigma
(+/- x counts)
As measured: TBD from burn-in
    - SSE Quantization Accuracy
Allocated: 0ū 3-sigma
Designed To: 14-bit accuracy
Results In: +/- 1.5e-12ū 3-sigma
    - SSE Noise
Allocated: 0ū 3-sigma
As Measured: [<1 count]
Results In: +/- 0.0153ū 3-sigma
    - SSE Temp Error
Allocated: 0ū 3-sigma
will know better after burn-in and cal
could be as low as unc of tc
    - Input Voltage to Transducer
Allocated: 0ū 3-sigma
Designed To: +/- 0.5V (MEDLI-RQ-78)
  - Manufacturing/Geometry Error
Allocated: <+/- 0.25ū 3-sigma
Designed To: [+/- TBD]
Results In: +/- TBDū 3-sigma
    - Port Location Knowledge Error
Allocated: +/- 0.05"
(MEDLI-FS-1434)
Results In: +/- 0.0367ū 3-sigma
    - Aeroshell Deflection Error
Allocated: 0ū 3-sigma
Designed To: +/- TBD"
Results In: +/- TBDū 3-sigma
  - Time Latency Errors
Allocated: 0ū 3-sigma
Jeff and Frank working
    - RCE Timing Error
Allocated: 0ū 3-sigma
Designed To: [+/- 10 ms]
Results In: +/- 0.15ū, 3 sigma
    - DPAM Timing Error
Allocated: 0ū 3-sigma
Designed To: [+/- TBD]
Results In: +/- TBDū, 3 sigma
    - SSE Timing Error
Allocated: 0ū 3-sigma
Designed To: [+/- TBD]
Results In: +/- TBDū, 3 sigma

Allocated: +/- 0.25° 3-sigma

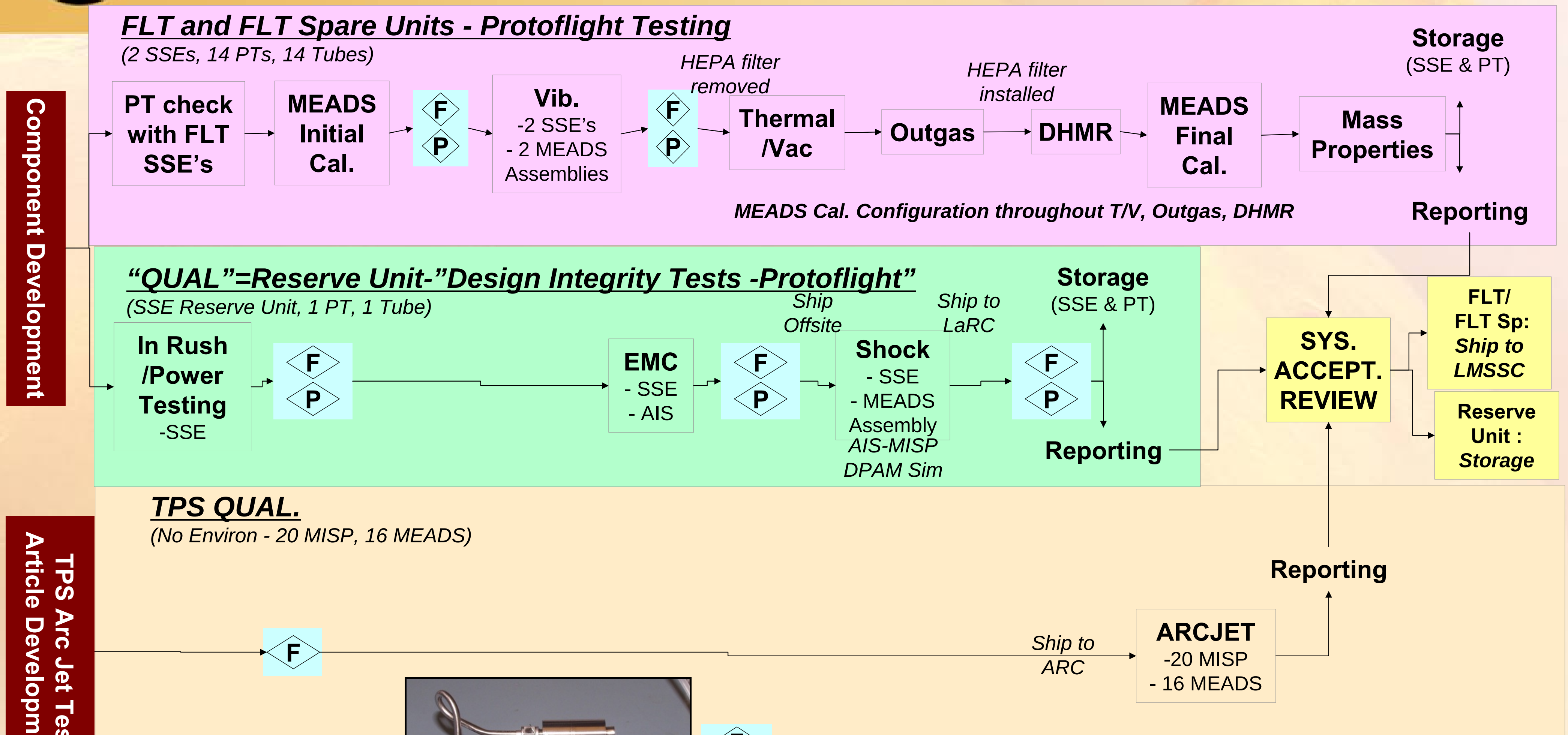
Pressure Transducer Performance

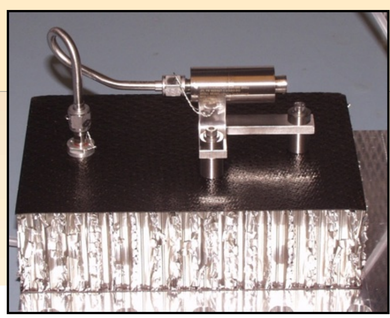
- Space-qualified pressure transducers have long lead times
- Requirements based on SEADS, but electronics were removed from pressure head (thermal)
- 2 vendors responded to solicitation: Tavis, Inc. (heritage) and Stellar Technologies, Inc. (STI)
- Both products purchased to reduce schedule risk (both received Oct 07)
- Vendors did vibration testing to MSL protoflight levels, with good results





MEDLI Protoflight V&V Test Plan 12/07*





F: Functional Test
P: Performance Test

Meads Cal Configuration in 6'x6' chamber-see diagrams
MEADS Assembly –PT with TC+tube on heat shield structure

*For planning purposes only

Predicted MEADS Flight Environment

- **Arcjet testing requirements come from CFD predictions of flight environment at pressure port locations, margined**

- **MSL 07-25 Trajectory, +3-Sigma Conditions**

Location	Pressure (atm)	Heat Flux (W/cm2)	Shear (Pa)	Heat Load (J/cm2)
P1	0.38	59	6	2200
P2	0.38	59	3	2300
P3	0.37	90	30	3700
P4	0.32	128	90	4500
P5	0.24	140	154	4600
P6 & P7	0.30	108	76	3600

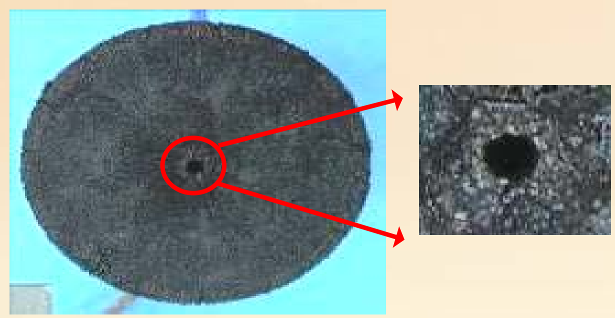
- ***These conditions ARE NOT the MSL margined flight conditions***

Ref: Karl Edquist

A Hole in the TPS??

- ***Must do adequate testing to prove that port hole will not cause TPS failure (and that we can get a good pressure measurement….)***
- All primary objectives were met during initial developmental arc-jet testing (June 2007)
  - No discernable degradation of port shape at SLA interface for each diameter
  - The amount of surface recession observed was minimal and will not invalidate pressure measurements
  - Demonstrated ability to measure pressure in SLA-561V
  - The bondline temperature for any model never exceeded the maximum allowable
  - Pyrolysis did not show an effect on the measurements at tested conditions; no sleeve needed

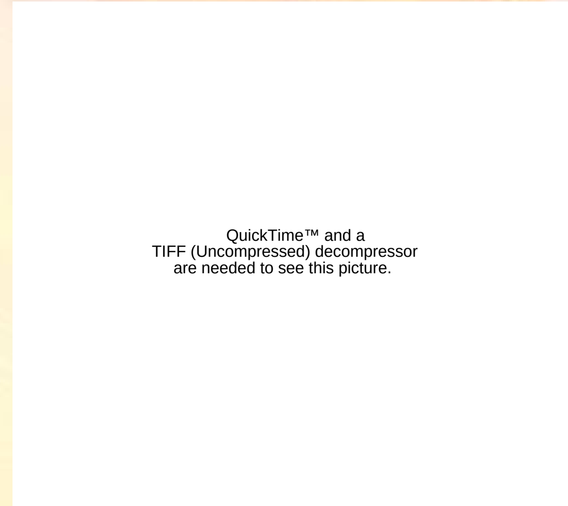
Boeing Large Core Arc Tunnel (LCAT)



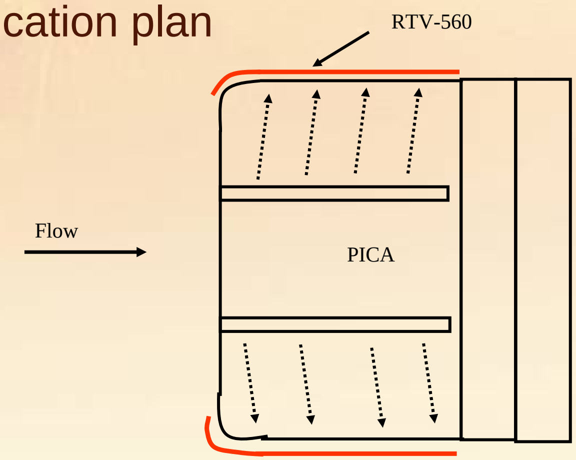
0.10" port hole in SLA-561V

A Hole in the TPS?? (cont'd)

- MSL switch from SLA-561V to PICA in October of 2007
  - Repeat stagnation testing
  - Shear testing
  - Qualification testing (stagnation and shear)
  - Must now be concerned about port location relative to seams
  - With MSL, defining acceptable hole shape change (bondline temperature still met)
- Challenges
  - Facility availability -- Boeing LCAT is becoming routine for MEADS
  - Synchronization with MSL TPS qualification plan
  - PICA porosity
  - High pressure, low heating case



Preliminary 0.04" - 0.10" port holes in PICA



MEADS Operational Thermal Predictions

MEADS Operating Temperature Range: -300ºC -> 200ºC

Qualification/Protoflight = 50ºC

+20C Margin

Allowable Flight Temp (AFT) = 30ºC

+5C Uncertainty

(Mars Entry) **25ºC**

Predicted Range (includes uncertainty of MSL inputs)

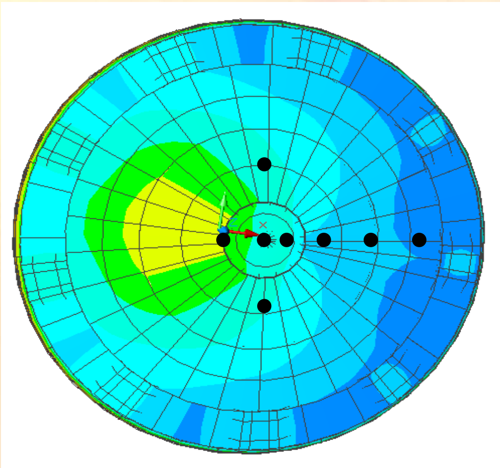
(Cruise Worst-Case Cold) **-85ºC**

Allowable Flight Temp (AFT) = -90ºC

-15C Margin

Qualification/Protoflight = -105ºC

Temperature range covers the minimum and maximum predicted temperatures of any transducer (does not represent the variation seen by a particular transducer).

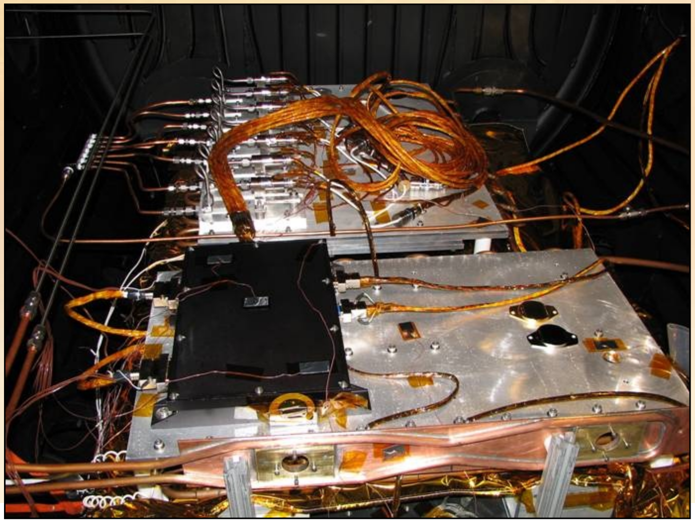


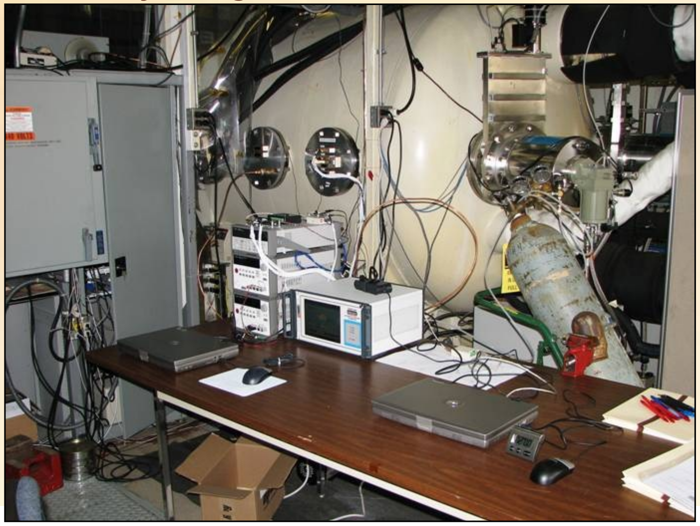
MEADS worst-case cold is derived from Lockheed Martin's coldest heatshield temperature prediction, including model uncertainty. No additional model uncertainty for MEDLI is necessary.

Ref: Kailtin Liles

Recent and Near-Term MEADS Activities

- Completed 9 days of calibration testing for the flight transducers and an SSE box
  - Thermal vacuum chamber operations
  - SSE and transducer temperature independently controlled
  - Series of 8-14 pressure points run at each temperature setpoint; data collected through SSE
- Vibe, shock of qual transducer completed
- Planning calibration of LCAT nozzle for shear testing in July, further stagnation testing with collared PICA models
- Qualification arcjet plans in work with MSL
- Delivery of 1 transducer for Heatshield #1 system tests - early August





Summary

- MEDLI instrumentation suite (finally!) will measure temperature, pressure, and recession of MSL entry vehicle's heatshield
- MEDLI will collect an order of magnitude more EDL data than all previous Mars missions combined, providing the community with a unique opportunity to validate models and improve predictions for missions to come
- MEADS is proving that a pressure measurement system can operate in an ablative environment
- Taking even a simple measurement system from paper to flight has extreme challenges! (but it's sure to be worth it…)
- There are and will continue to be lots of lessons learned for the next time